(12) UK Patent Application (19) GB (11) 2 309 562 (13) A

(43) Date of A Publication 30.07.1997

(21) Application No 9701296.7

(22) Date of Filing 22.01.1997

(30) Priority Data
(31) 9601461 (32) 26.01.1996 (33) FR

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(51) INT CL^6
G06F 17/00 , G01V 1/28 , G06F 17/13

(52) UK CL (Edition O)
G4A AUA

(56) Documents Cited
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Inspec Abstract Accession No 02723383 & Journ. Geodynamics, Vol 3, No 1-2, July 1985, pp 155-168
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(58) Field of Search
UK CL (Edition O) G4A AUA AUXX
INT CL^6 G01V 1/28 1/30 1/40 3/38 9/00 11/00 , G06F 17/00 17/13 17/50
Online: COMPUTER, INSPEC, Dialog/GEOPHYS, WPI

(54) Modelling the filling of sedimentary basins

(57) The method relates to the construction of a numerical deterministic model of the diffusive type allowing the filling of sedimentary basins by siliciclastic and carbonate sediments to be simulated in 2-D or 3-D. On the basis of known data pertaining to the architecture of a basin and measurement data, well loggings, seismic surveys, etc., a set of input data is produced relating to the accommodation structure made available by subsidence and eustasy, the inflow and production of fluviatile or marine sediments and physical transportation parameters such as the diffusion coefficients of the different lithologies. This set of data is applied to a numerical model. The results that can be derived therefrom as regards the geometry and lithologies of the sedimentary units are compared with measurement data and the input data are iteratively fined down, step by step, by a process of inversion. The model constructed in this manner allows the volumetric partitioning, distortion of the genetic units or sedimentary geometries observed, for example, to be reproduced.

Figure 1

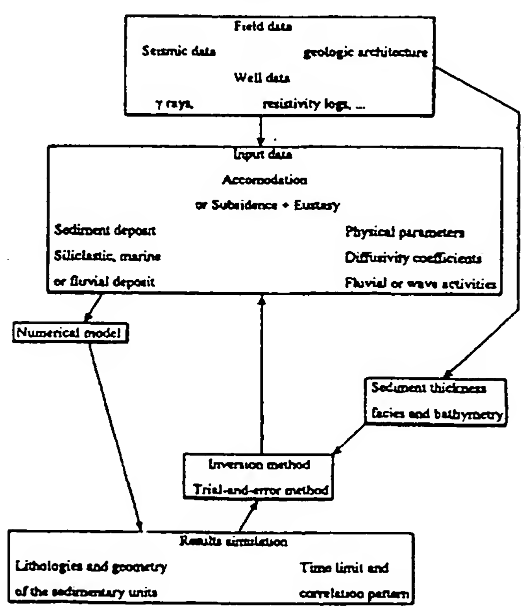

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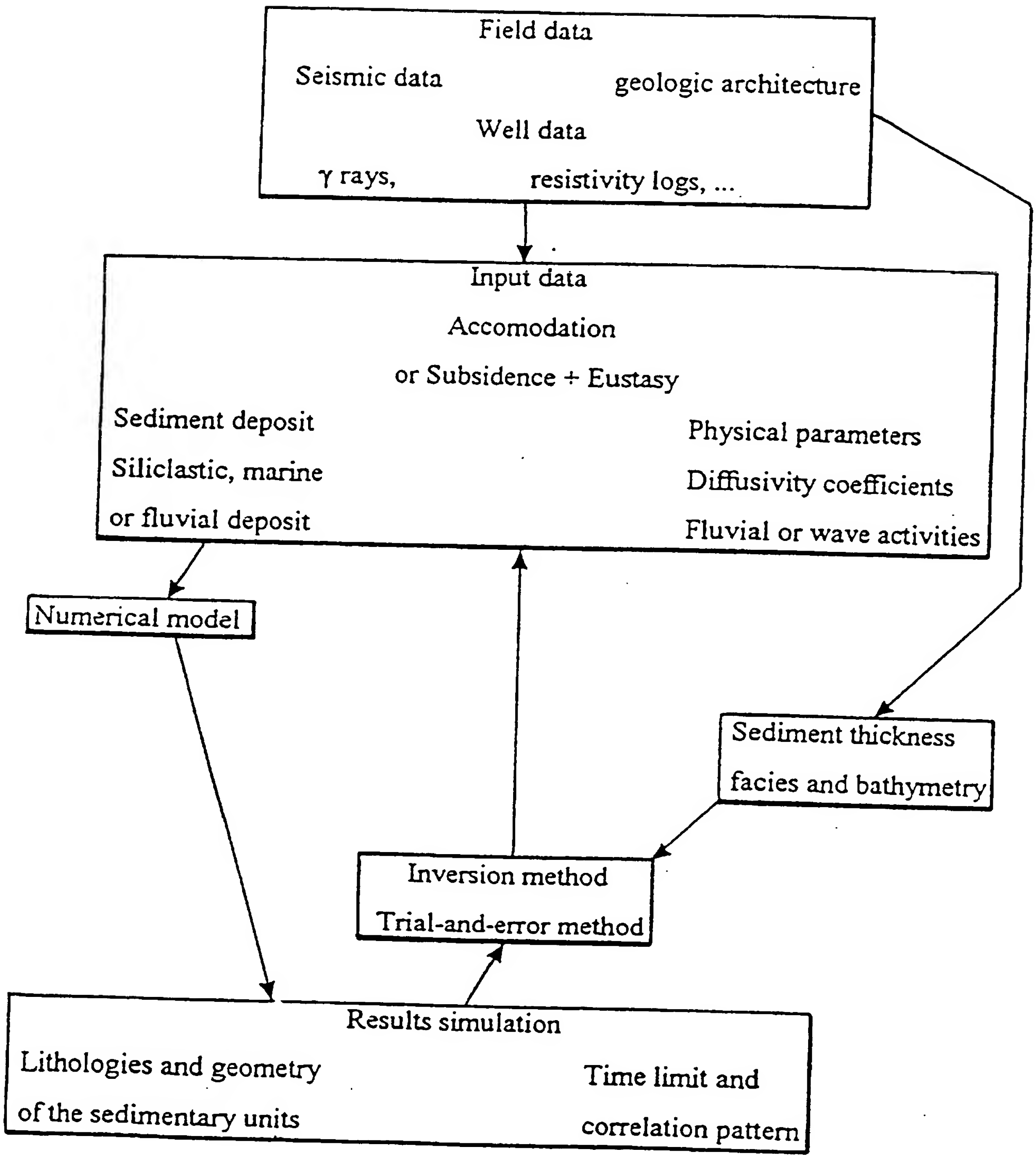
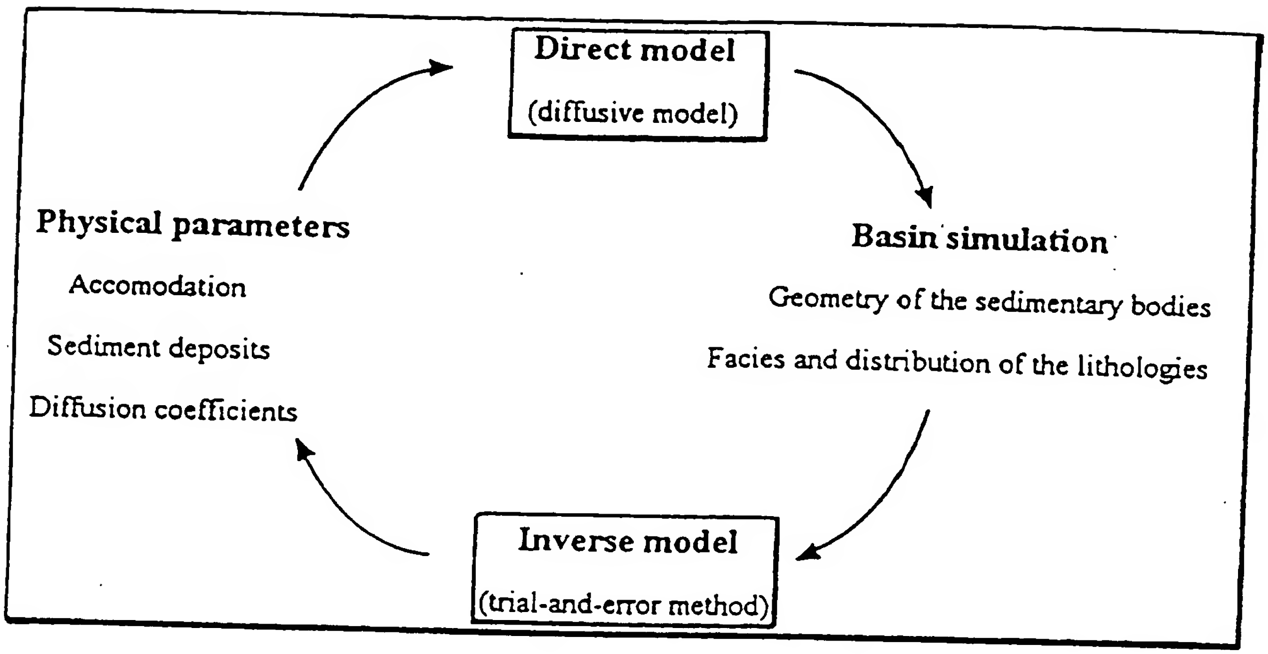
Figure 1



Field data
Seismic data
geologic architecture
Well data
γ rays,
resistivity logs, ...
Input data
Accomodation
or Subsidence + Eustasy
Sediment deposit
Siliclastic, marine
or fluvial deposit
Physical parameters
Diffusivity coefficients
Fluvial or wave activities
Numerical model
Sediment thickness
facies and bathymetry
Inversion method
Trial-and-error method
Results simulation
Lithologies and geometry
of the sedimentary units
Time limit and
correlation pattern

Figure 2


Direct model
(diffusive model)
Basin simulation
Geometry of the sedimentary bodies
Facies and distribution of the lithologies
Inverse model
(trial-and-error method)
Physical parameters
Accomodation
Sediment deposits
Diffusion coefficients

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METHOD FOR SIMULATING THE FILLING OF A SEDIMENTARY BASIN

The objective of the present invention is a method for building a model to simulate the sedimentary filling of basins on large scales in terms of time and space.

The method of the invention relates more specifically to the creation of a numerical stratigraphic model that will allow multi-lithological filling of a basin to simulated in two or three dimensions (2-D or 3-D), the purpose being to simulate the stratigraphic response of the sedimentary system to variations over time in the eustasy, subsidence, sedimentary deposits as well as the physical parameters governing the inflow of sediments to the basin.

BACKGROUND OF THE INVENTION

Recent progress in the field of geology, from which seismic stratigraphy followed by genetic stratigraphy has grown, has profoundly changed our understanding of how basins have filled up with sediment on large scales of time and space, by demonstrating the primordial effects of three main parameters: eustasy, tectonics and sedimentary flux.

Numerous models, in particular numerical deterministic models, have been created as an aid to understanding the geometric and lithological implications of these new approaches.

These numerical models simulate the transportation and depositing (or erosion) of sediments in the basin by applying a more or less complex description of the nature of subsidence and the inflow of sediment based on an estimated eustasy. It should be recalled that the term eustasy is used to refer to variations recorded in the surface of the oceans simultaneously across the whole of the earth's surface whilst the term subsidence is used to refer to the absolute displacement of the bottom of a sedimentary basin relative to a fixed marker level over time. These models therefore enable the effects of

different theories (the relationship between climate and eustasy, etc.) on the layout of sedimentary units to be tested. In addition, when applied to real situations, they enable the consistency of parameters incorporated in the model, such as eustatic and tectonic variations, to be tested and the geological interpretation of the basin under study to be confirmed.

A model is expected to be able to define the major trends in variations of the facies (variation in the sand/clay ratio, carbonate content, etc.) within genetic units. A multi-lithological model-building system is needed for this purpose. The model must be capable of simulating the transportation and sedimentation of different siliciclastic (sand, clay, etc.) and carbonate lithologies (reef, deep-sea carbonate mud, bioclasts, etc.) so that these trends in facies variations are generated by the model, irrespective of the given geological conditions, such as the sandy alluvial plain and clayey marine area. In this ideal model, the siliciclastic sediments are brought into the basin by rivers and sea currents. The carbonates are produced in the marine area in accordance with a law based on the bathymetry and turbidity of the water.

$$P = P_o A_{turb.} e^{-kz}$$

P productivity of carbonates

P_o optimum productivity

$A_{turb.}$ attenuation factor depending on the turbidity (turb.) of the water

e^{-kz} attenuation factor depending on the bathymetry (z).

Once they have been brought to the level of the basin boundaries or produced in the basin, the sediments are transported and settle.

Three major families of deterministic models govern the transportation of sediment:

- particulate models based on solving the motion of particles (calculation of the water flow followed by

the relationship between the water flux and the flux of sediments);

- diffusive models based on an equation of diffusion in which the diffusion coefficient can be more or less precisely defined (taking account of several lithologies, the water flux, the environment in which deposits are being made, etc.); and
- geometric models based on a definition of the geometric profile of the environment in which the deposits are occurring (length and incline of the alluvial plain, etc.) or on a geometric definition of the rate of sedimentation (exponential decrease in the marine area, etc.).

Particulate models use a careful definition of the sedimentary process and are therefore as chaotic as nature. Basically, they allow simulations to be produced on the scale of a reservoir (length approximately 0.5 to 50 km and duration of 5 to 500 ka). Diffusive and geometric models both provide more or less rough approximations of the natural processes. They are much more stable than the real situation they are intended to portray and provide only a toned-down approximation of nature. These models are applied by preference on the scale of the basin (length approximately 10 to 1,000 km and duration of 0.1 to 10 Ma).

Geometric models, based on an approximation of the morphology of basins, are mainly applied to straightforward 2-D cases, in which subsidence, the nature of the sediments and climate do not affect the definition of the equilibrium profile too extensively.

More general in nature, diffusive models, based on an approximation of the physics of sediments, are applied in 3-D and are capable of processing transportation and sedimentation of multiple lithologies.

Various known diffusive models are described, for example, by:

- Kenyon and Turcotte, 1985, Morphology of a delta

prograding by bulk sediment transport, in *Geol. Soc. Amer. Bull.*, 96, 1457-1465.

- Begin, Z.B., 1988, Application of a diffusion - erosion model to alluvial channels which degrade due to base-level lowering. Earth Surface Processes and Landforms, 13, 487-500.
- Rivenaes, J.C., 1988, Application of a dual-lithology, depth dependent diffusion equation in stratigraphic simulation, Basin Research, 4, 133-146.

One advantage of diffusive models is that they allow a return to geological concepts because they quantify relations such as the variable duration of progradation and retrogradation phases of genetic units or changes in the sandiness either on the basis of the bathymetry or the prograding or retrograding tendency of the littoral.

The purpose of the known models is essentially that of numerical experimentation with theoretical concepts along 2--D profiles.

The modelling method of the invention makes it possible to build a deterministic model of the diffusive type in 2-D or 3-D, which simulates the multi-lithological filling of a sedimentary basin. It uses known field data pertaining to the basin architecture and measurement data such as well-logging or seismic data to make up a set of input data relating to a space made available by subsidence and eustasy, the depositing of fluviatile or marine sediments and the transportation thereof, and physical parameters such as the diffusion coefficients of the various lithologies. The method is characterised in that it comprises, by a process of iteration:

- dividing the basin into grids of regular dimensions,
- solving large-scale diffusive transport equations in accordance with an explicit pattern of finite volumes and constant time intervals, so as to simulate the flux of each lithology deposited on each grid; and
- comparing the simulation results with the field data and modifying the input data step by step by a process of

inversion.

The inversion step may be performed by a process of trial and error.

The diffusive model produced provides an understanding in 3-D as to how a basin is subjected to multi-lithological filling and therefore tests the consistency of a data base or even helps to predict the position and the geometry of sedimentary bodies. It gives a realistic prediction of the thicknesses of sedimentary bodies and facies. These parameters, adjusted to the well data, therefore make it possible to refine what is known about the basin overall by pinpointing the location and quality of bodies that are likely to be hydrocarbon reservoirs.

Since, in order to re-construct the sedimentary geometries, the model of the invention requires that the physical parameters be accurately re-constructed on a large scale (flux quantification, diffusion coefficients, etc.), it is necessary to identify which links will have to be defined between accommodation structure, sedimentary deposit and diffusion coefficient in order to re-construct the geometries observed and hence the proposed pattern of correlation of the well data. The geological consistency or non-feasibility of these various links will therefore make it possible to confirm or invalidate the selection of one pattern of correlation as opposed to others.

Other features and advantages of the method of the invention will become clear from the following description and with reference to the appended drawings, in which:

- Fig. 1 illustrates the modelling process; and
- Fig. 2 illustrates a model optimisation pattern by a process of trial and error.

The deterministic model is constructed in a series of successive stages. In a first stage, the accommodation structure for the sediment is defined. The sediments are then introduced and sedimentary production in the basin is simulated. These sediments are then distributed in

accordance with the laws of macro-transport, which will be defined in the description below, limiting erosion to the weathering layer.

1) <u>Creating the accommodation structure</u>

The space available for the sedimentary filling of the basin is the sum of the eustasy and subsidence. It was decided that this would be defined point by point, either on the basis of eustatic curves and subsidence maps or directly from maps of accommodation structures, without therefore using any physical models linking the eustasy with climate or subsidence with tectonic, isostatic or thermal processes.

Although it does not modify the accommodation structure, compaction affects sedimentary filling by altering the thickness of sedimentary layers. In order to take account of mechanical compaction, it was decided that the porosity of the sediments would be directly linked to the maximum burial reached thereby, using a relationship of exponential form which would provide a good approximation of the compaction, as defined by

- Beaudoin *et al*, Mesure directe de la compaction dans les sédiments, *In:* Berthon, J.L., Burollet P.F., and Legrand, Ph. (eds). *Genèse et évolution des bassins sédimentaires*. Notes et Mémoires No. 21, Total - Compagnie Française des Pétroles.

In order to take account of the case of multi-lithology sediments, it was assumed that each lithology had a porosity independent of the others, which amounts to likening the sedimentary layers comprising a mixture of several lithologies such as sand and clay to a superposition of multiple sub-layers made up of pure lithologies. The porosity linked to each lithology is therefore dealt with individually as a function of the maximum burial reached by the sedimentary layer.

for each lithology i $\Rightarrow \Phi_i = \Phi_{r,i} + (\Phi_{o,i} - \Phi_{r,i}) e^{-z/z_i}$

where
- Φ_i porosity of the lithology (in %)
- $\Phi_{r,i}$ residual porosity of the lithology i (in %)
- $\Phi_{c,i}$ deposit porosity of the lithology i (in %)
- z maximum burial reached by sedimentary layer studied (in m)
- z_i reference burial of the lithology (in m).

In particular, this definition of porosity linked to the lithologies allows the individual transport of each lithology to be simulated and its effects on the porosity of the sedimentary layers to be deduced therefrom.

II) Introducing and producing sediments

Having created the accommodation structure in this way, the second stage of building the required model is to introduce sediments into the basin or produce them within the marine area.

1) Introducing sediments into the area studied

In geological terms, the flux of sediments at the boundaries of the area under study represent the deposits of sediment responsible for filling the basin. They can be physically perceived in terms of sediment flux boundary conditions.

These boundary conditions are fixed either by imposing the exact value of the flux in one sector of the boundary or by imposing continuous change on the sediment flux. The first of these instances represents a deposit zone imposed by conditions outside the basin, such as the outlet of a river draining a river basin external to the basin. The second of these cases represents a free zone along which the sediment flow is governed by the physical parameters within the basin, such as the characteristics of the waves. When simulating a basin, it is possible to combine these two types of boundary conditions, making a distinction between a continental zone, for example, where the flux is imposed by external fluvial deposits and a marine zone in which the flux is defined by the laws of

internal transport.

b) Sedimentary production inside the area studied

The sediments may also be produced inside the basin and more particularly so in the case of carbonate sediments. For the purposes of this modelling phase of the invention, it was decided that this process of production would be simulated with the aid of an empirical formula linking the production rate at each point of the basin to the bathymetry and the sediment flux as defined, for example, by

- Lawrence *et al.*, 1990, Stratigraphic simulation of sedimentary basins: concepts and calibration in *Amer. Assoc. Petrol. Geol. Bull.*, 74, 3, 273-295.

for each lithology i ⇒ $$\boxed{P_i = P_{0,i} B_i \prod_{j \neq i} F_{j,i}}$$

where

P_i production rate of the lithology I (in m/s)

$P_{0,i}$ maximum production rate of the lithology I (in m/s)

influence of the bathymetry

$$B_i = \begin{cases} 0 & \text{if } b \le 0 \\ \dfrac{b}{b_i} & \text{if } 0 < b \le b_i \\ e^{\beta_i (b - b_i)} & \text{if } b > b_i \end{cases}$$

B_i influence of the bathymetry (dimensionless)

b bathymetry (in m)

b_i bathymetric threshold (in m)

β_i attenuation coefficient (in m^{-1})

influence of the lithology

$$F_{j,i} = \begin{cases} 1 & \text{if } Q_j \le S_{j,i} \\ e^{-\gamma_{j,i}(Q_j - S_{j,i})} & \text{if } Q_j > S_{j,i} \end{cases}$$

$F_{j,i}$ sensitivity of lithology i to lithology flux j

Q_j flux of the lithology j (in m^2/s)

$S_{j,i}$ inhibition start threshold (in m^2/s)

$\gamma_{j,i}$ sensitivity coefficient (in $m^{-2}.s$)

In order to take account of the erosion of reefs when these are emerged, the process of mechanical weathering of these reefs was simulated by assuming that any reef sediment located in the weathering layer in the continental area would be transformed into a "bioclastic" sediment. The reef and bioclastic lithologies are transported into the basin in the same way as the siliciclastic sediments.

III) Sediment transport

Having defined the accommodation structure and quantity of sediment that must fill the basin, the model distributes the sediments across the entire basin in accordance with the laws governing large-scale transport, established by building on known transport laws, allowing an estimate to be produced for the flux of each lithology flowing into the basin at all points.

$$\begin{cases} \text{diffusion equation} & Q = -K\dfrac{\partial h}{\partial x} \\ \\ \text{conservation of mass} & \dfrac{\partial h}{\partial t} = -\dfrac{\partial Q}{\partial x} \end{cases}$$

where $\begin{cases} Q & \text{sediment flux (in } m^2\text{/year)} \\ K & \text{diffusion coefficient (in } m^2\text{/year)} \\ h & \text{altitude of the point studied (in m).} \end{cases}$

The rate of sedimentation or erosion is defined by linking these laws to the principles of conservation of mass. However, this sedimentary transport is limited to the weathering layer and the erosion velocity at a given point may not exceed the local weathering velocity.

Creating a large-scale transport law in 3-D

The law of small-scale continental transport given above represents flows of water and sediments on time-scales ranging from a few hours to a few months and space scales in the order of several square kilometres. In order to be able to apply these laws to large scales of time and space, it was necessary to convert them into large-scale transport laws.

To move from the small-scale continental area in two dimensions to the basin as a whole on a large scale and in three dimensions, it is necessary to:

- take account of the diversity of flows in the

continental area ranging from the minimum low-water patterns where the water is directed into channels through to the flood patterns where the water spreads across all the flood plains;

- in the marine area, extrapolate a transport law validated for the continental area and define how the action of the waves will be simulated;
- describe the differential but simultaneous transport of several lithologies; and
- take account of the limited availability of sediment.

Expressing the law of fluvial transport in 3-D

In order to express this law of transport in three dimensions and take account of the various water flow patterns, from flooding down to low-water levels, it was assumed that the flux of sediment at any point was a continent proportional to an intrinsic diffusion coefficient, the flux of water and the incline of the basin.

The water flux, constant during the study of small-scale transportation of sediments in two dimensions, now incorporates the variability over time of the different water flow patterns. Three basic flow models have been defined.

a) The straight flow corresponds to the situation where the water arriving at a given point of the basin is entirely re-distributed in the direction of the largest incline and where the time interval separating two simulation instants is short relative to the period of over which changes occur in the course of the water. This period is equivalent to the meandering period if the basin is studied using extremely fine grids of a size of about one hundred metres and is equivalent to the avulsion period if the grids are about one kilometre. A water flow of this type gives rise to a flow of sediment in a single direction at each instant.

b) What is referred to as "wild" flow corresponds more specifically to the situation of large-scale

transportation of sediment, where the simulation time period used is about a millennium. It is therefore longer than the period during which changes occur in the course of the water. For this type of flow, it can therefore no longer be assumed that an individual stream has kept to a single direction over the period and it becomes necessary to take account of the different courses that the water might have followed. In addition, unlike the laws governing small-scale transport, which focus on a single flow pattern, such as the flood pattern or low-water mark pattern, the large-scale transport law must take account of each of these regimes in order to reproduce accurately both the flood process, where clays are deposited on the flood plains, and the low-water level process, where fluviatile incision occurs and the sediments are rapidly transported towards the delta area.

In the case of a wild flow of this type, it is assumed that the water has followed all those directions in space having a positive incline. However, the choice of these directions is made at each instant by taking the path of greatest incline. This being the case, it must be assumed that the probability of choosing one direction rather than another is equal to the ratio of the incline of this direction to the sum of all the inclines. The greater the incline of one direction relative to the other directions, the greater chance there is that the water will flow in this direction. This wild flow is the average of all the straight flows occurring over the course of the simulation period.

c) Uniform flow corresponds more specifically to the case where the reasoning outlined above is generalised by applying a mega-time scale of one hundred thousand years. In this case, it can be assumed that the relief has reached a state of equilibrium. The flow of water therefore becomes uniform and there are no areas of more prevalent flow such as an incised valley or a belt of meandering. Water flow of this type gives rise to a

uniform diffusion of sediment.

These three flow types, all combinations of which are possible, therefore represent three ways of looking at the drainage system of a basin over different lengths of time. These flows correspond to the changeover to the average of the straight flows, giving rise to wild flow, and the wild flow giving rise to uniform flow.

In order to take account of the fact that within the wild and uniform flow modes the flux of water does not take a single direction but an infinity of probable directions, it was decided to replace the term water flux, which implies direction, with the term water efficiency. This water efficiency was then standardised by dividing the water flux by a reference flux.

Extrapolation to the marine area

A law of transport applicable to the marine area was also chosen. To this end, the various types of sediment transport were classified as a function of the origin of their motive energy, making a distinction between "gravity" flows drawing their kinetic energy from a transformation of the potential energy of the water flow and flows induced by the movement of waves due to the action of winds.

It was verified that gravity flows of sediment could be simulated by a diffusion equation of the same type as that defined by Kenyon and Turcotte, 1986, mentioned above.

Similarly, three types of flow were considered, the first being straight flow where the water is channelled at each instant, wild flow where the average water flow is considered by taking account of the distribution of water in the calculation and uniform flow which gives rise to a uniform distribution of sediments leading to regression of the littoral in the sector located near to the mouth of the delta.

The choice of flow type depends on the value of the interval separating two simulation instants and the

fluvial hydro-dynamism of the basin. If the time interval is short or the hydro-dynamism high, it is necessary to simulate a straight flow. A wild, even uniform flow, on the other hand will enable the envelope of sedimentary bodies to be represented.

In order to construct the model of the invention, empirical extrapolation of the diffusion equation to the basin as a whole is assumed to be valid for "gravity" flows.

Wave-induced sediment transportation

As with fluviatile flows, it is possible to combine the laws governing fluid mechanics in order to obtain a small time-scale law (a few days to a few months) that will describe wave-induced sediment transport. On the other hand, it is not possible to extrapolate such a law on large time scales. It is extremely difficult to re-construct the exact morphology of the oceans at each stage of sedimentary filling and thus define a complete geological model. For this reason, empirical laws describing changes in the littoral on a large time scale were used, linking the sediment flow induced by waves to local parameters such as the incline of the basin and the local characteristics of the waves.

Wave-induced marine transportation orthogonal to the littoral

In the model, sediment transportation to the shoreline is simulated by a diffusion equation and is incorporated in the fluvial transport system described above with the aid of a negative diffusion coefficient representing the braking effect of the waves on fluvial transportation. Because of the problems of physical and numerical stability of the sedimentary system, it was assumed that the waves slow down the movement of sediment towards the open sea but are unable to generate a residual flux of sediment towards the coast on the millennium scale, which means that this braking effect can never reverse the direction in which the sediment is

transported. In order to account for the reduced activity of the waves in the direction of the open sea, it was assumed that the coefficient decreases exponentially with the bathymetry.

Wave-induced longshore drift

An empirical relationship linking the sediment flux flowing at a given point to the total energy of the wave motion and to an attenuation factor linked to the bathymetry was used as a means of quantifying longshore drift so as to use only local parameters.

Simultaneous transport of several lithologies

The large-scale laws of transport mentioned above were established for a soil comprising a single lithology. In order to take account of a situation where multiple lithologies are transported simultaneously, the following relationships were used, incorporating relative diffusion coefficients:

for each lithology i

diffusion ⇒ $$\boxed{\vec{Q}_i = v_i K_i E_{water} \vec{\nabla} h}$$

where

$\vec{Q}_i$	flux of the lithology I (in m^2/s)
v_i	lithology I content (dimensionless)
K_i	diffusion coefficient relative to the lithology I (in m^2/s)
E_{water}	water efficiency (dimensionless)
h	altitude of the ground surface (in m).

and $K_i = K_{fluv,i} - K_{waves,i}$

These large scale transport equations are linked to the theory of conservation of mass, applied to each lithology so as to define at each point of the basin the rate of erosion or sedimentation and the content in each of the lithologies.

Sediment availability and the weathering layer

In order to take account of the uneven diffusion capability of the sediments of each lithology, it was assumed that, as already described by Rivenaes, J.C.,

1988m, op.cit., there is a layer of constant thickness (decimetric, for example) in which sediment transport takes place. The sediment flux is then proportional to the lithological contents of the weathering layer.

In order to construct the model of the invention, it was decided that the weathering velocity, or the speed at which this superficial weathering layer is created at each point of the basin, would be estimated by means of an empirical relation.

In view of the above, it was decided that for the purposes of building the model of the invention, the following two empirical large-scale transport laws would be used, the first relating to diffusive transport and the second to shore-line transport:

for each lithology i

littoral drift $\Rightarrow$ $\boxed{Q_s = K_{l,i}\, E\, C_g\, f(b) \sin\alpha \cos\alpha\, \vec{\tau}}$

where $f(b) = \begin{cases} b/b\beta & \text{if } b \le b\beta \\ e^{-a(b-b\beta)} & \text{if } b > b\beta \end{cases}$

Q_s flux of the lithology i induced by littoral drift (in m^2/s)

$K_{l,i}$ efficiency of the transport of the lithology i by the waves

E density of the wave energy $\left(= \frac{1}{8} \rho_e g H^2\right)$

C_g rate of propagation of the wave energy

$f(b)$ flux distribution function as a function of the bathymetry

α angle of approach of the waves

Numerical solution

In order to construct the model of the invention, the numerical solution to transport equations based on a discrete treatment of the basin under study in space and a discrete treatment of the formation in time has to be found.

The basin studied is divided into square grids of a constant size, whilst the filling of each grid is

simulated on the basis of a succession of calculating times, separated by a constant time interval. The width of the grids is from 1 to 10 kilometres, depending on the size of the basin being simulated, whilst the time interval is in the order of 50,000 years.

The transport equations are then solved using an explicit numerical pattern in which the physical parameters such as flux or altitude at the time (n+1) are expressed as a function of parameters measured at the time (n), the values of which are therefore known.

In the case of a single lithology in two dimensions, this solution is expressed as follows:

$$(1)\quad Q = -K\frac{\partial h}{\partial x} \quad \Rightarrow \text{ in each grid i } \quad Q_i^{(n+1)} = -K_i\frac{h_{i+1}^{(n)} - h_i^{(n)}}{dx}$$

$$(2)\quad \frac{\partial h}{\partial t} = -\frac{\partial Q}{\partial x} \quad \Rightarrow \text{ in each grid i } \quad \frac{h_i^{(n+1)} - h_i^{(n)}}{dt} = -\frac{Q_i^{(n+1)} - Q_{i-1}^{(n+1)}}{dx}$$

$$\text{i.e. } \quad h_i^{(n+1)} = h_i^{(n)} + \frac{dt}{dx^2}\left(K_i^{(n)}\frac{h_{i+1}^{(n)} - h_i^{(n)}}{dx} - K_i^{(n)}\frac{h_i^{(n)} - h_{i-1}^{(n)}}{dx}\right)$$

$$\begin{cases} h_i^{(n)} & \text{altitude of the grid i and at the time n (in m)} \\ K_i^{(n)} & \text{diffusion coefficient at the level of the grid i (in } m^2/s) \\ Q_i^{(n)} & \text{flux of sediments between the grids i and i+1 (in } m^2/s) \\ dt & \text{time interval (in s)} \\ dx & \text{grid width (in m)} \end{cases}$$

However, this rather simple form of expression becomes more complex as we move to a situation of multiple lithologies in 3-D and once the restriction on the transportation of sediment to the weathered layer is taken into account. In such a case, it can be said that:

$$\frac{\partial h}{\partial t} = -V_t \max, \quad \text{i.e.}$$

$$h_t^{(n+1)} = h_t^{(n)} - V_t . dt$$

Explicit solution by finite volumes is the fastest calculating method. Furthermore, it provides very accurate results as long as it remains within the stability range of the algorithm, which requires very short internal calculating time intervals in the order of a century to a millennium.

By applying the model to the input data set up from the field data, it is possible to simulate the transport of sediment across the entire basin being studied.

The validity of the simulation is then tested by matching the results provided by the model with the data compiled in the field, mainly the thicknesses of the sediments and the facies observed on well logs.

If there is a discrepancy, the set of input parameters for the model is sought by a process of inversion - accommodation structure and quantity of sediment transported - so that the difference between the results produced by these parameters and the constraints imposed are minimal, as illustrated below.

direct model $\Rightarrow$ $S=M(p)$

difference function $\Rightarrow$ $E(p) = \|S-d\|$

p	whole of the input parameters of the model
M	whole of the equations governing the model
S	whole of the results at the model output
C	whole of the geological constraints
E	difference function between the results and the constraints
$\|x\|$	measurement of the different between results and constraints

inversion $\Rightarrow$ find $\tilde{p}$ such that

$\tilde{E}=E(\tilde{p})$ is the absolute minimum of the function E

$$\forall p, \; E(p) \geq \tilde{E}$$

Within the context of the present method, the purpose of the inversion process is to quantify in particular the values of the accommodation structure, the sedimentary

inflow and the diffusion coefficients in order to produce a simulation in which the geometries of the sedimentary bodies as well as the measured thicknesses and facies directly below the calibration wells are as close as possible to the geological constraints.

A method of the trial and error type is used. A set of initial parameters is defined. The solution to the model linked to these parameters is calculated and the value of the parameters modified as a function of the discrepancy between the solution and the geological constraints. This process is continued until the discrepancy becomes sufficiently low.

Once the optimum concordance has been reached, the simulation will provide quantitative data pertaining to the geometry of the basin and the lithologies of the sedimentary units. It will also provide a means of checking that the correlation pattern of the wells is consistent.

Geological validation of the model obtained:

The validity of the model produced in this manner was tested on simple two- and three-dimensional theoretical examples. It was assumed that the subsidence velocity, the rate of sedimentary inflow and the diffusive action of the sediments were constant. By defining the eustasy in accordance with one or two orders of cyclicity, these simple but realistic examples were used to demonstrate that the diffusive model is capable of representing the implications of theories of genetic stratigraphy, such as the volumetric partitioning of the sediments within a genetic unit and the distortion of the genetic units. The geological consistency of the results of these simulations is such that it provides empirical validation for the use of the multiple-lithology diffusion equation on large time and space scales.

The model was also tested on real situations. The size of the sedimentary objects simulated was typically on the scale of a reservoir - Mesa Verde Group of the San

Juan basin (Colorado, USA) - for example, and on the scale of a basin - the lower Cretaceous of the Paris Basin - and the inversion method was used to define the parameters of the model (accommodation structure, sedimentary inflows and diffusion coefficients) based on geological constraints (thicknesses and facies of the sedimentary layers) by means of the trial and error method.

This inversion, coupled with the non-dimensioning theory of the diffusion equation produces simulations from which the results are adjusted to the geological constraints. It was verified that the diffusive model used does produce very accurate simulations, with mean differences for the cumulative thicknesses of the sediments of some 5 metres to 25 kilometres away from the constraint wells (for a formation of an average thickness of 100 metres) and a difference of less than 10 kilometres (the size of the calculating grids was 10 kilometres) between the position of simulated and observed shores.

As a result of this geological and faciological re-construction and the fact of having access to the physics of sedimentary processes on a large scale, the diffusive model of the invention allows a return to the geological data bases in that it fines down the values of the bathymetry and sediment flux, for example, by re-producing changes in the accommodation structure over time and by confirming or invalidating the selection of a pattern of correlation.

CLAIMS

1. A method of constructing a deterministic model of the diffusive type, which allows the multi-lithological filling of a sedimentary basin to be simulated, in which, on the basis of known field data pertaining to the architecture of the basin and measurement data as well as well logging data or seismic data, a set of input data is set up relating to an accommodation structure brought about by subsidence and eustasy, the inflow of fluviatile or marine sediment and the transport thereof, and physical parameters such as the diffusion coefficients of different lithologies, wherein, by a process of iteration, it consists in: dividing the basin into grids of regular dimensions; solving large-scale diffusive transport equations in accordance with an explicit pattern of finite volumes with constant time intervals, so as to simulate the flux of each lithology deposited on each grid; and comparing the results of the simulation with the field data and modifying the input data step by step by a process of inversion.

2. A method as claimed in claim 1, wherein the inversion stage is performed by a process of trial and error.

3. A method as claimed in claim 1 or 2, wherein the large-scale diffusive transportation of each lithology is modelled by the relationship:

for each lithology i

diffusion $\Rightarrow$ $\boxed{\vec{Q}_i = v_i K_i E_{water} \vec{\nabla} h}$

where
- $\vec{Q}_i$ flux of the lithology I (in m^2/s)
- v_i lithology I content (dimensionless)
- K_i diffusion coefficient relative to the lithology I (in m^2/s)
- E_{water} water efficiency (dimensionless)
- h altitude of the ground surface (in m).

and $K_i = K_{fluv,i} + K_{waves,i}$

4. A method as claimed in one of the preceding claims, wherein the littoral transport of each lithology is modelled on a large scale by the relationship:

for each lithology i

littoral drift $\Rightarrow$ $\boxed{Q_{s} = K_{l,i}\, E\, C_{g}\, f(b) \sin\alpha \cos\alpha\, \vec{\tau}}$

where $f(b) = \begin{cases} b/b_\beta & \text{if } b \le b_\beta \\ e^{-(b-b_\beta)} & \text{if } b > b_\beta \end{cases}$

Q_s	flux of the lithology i induced by littoral drift (in m^2/s)
$K_{l,i}$	efficiency of the transport of the lithology i by the waves
E	density of the wave energy $\left(= \frac{1}{8} \rho_e g H^2\right)$
C_g	rate of propagation of the wave energy
$f(b)$	flux distribution function as a function of the bathymetry
α	angle of approach of the waves

5. A method as claimed in one of the preceding claims, wherein the multiple-lithology sedimentary layers are defined as consisting of a superposition of lithologies with porosities regarded as being independent of one another.

6. A method as claimed in one of the previous claims, wherein the introduction and production of sediments is modelled using a relationship such as:

for each lithology i $\Rightarrow$ $\boxed{P_i = P_{0,i} B_i \prod_{j \neq i} F_{i,j}}$

where

P_i	production rate of the lithology I (in m/s)
$P_{0,i}$	maximum production rate of the lithology I (in m/s)

<u>influence of the bathymetry</u> $B_i = \begin{cases} 0 & \text{if } b \le 0 \\ \dfrac{b}{b_i} & \text{if } 0 < b \le b_i \\ e^{-\beta_i (b-b_i)} & \text{if } b > b_i \end{cases}$

B_i	influence of the bathymetry (dimensionless)
b	bathymetry (in m)
b_i	bathymetric threshold (in m)
β_i	attenuation coefficient (in m^{-1})

<u>influence of the lithology</u> $F_{i,j} = \begin{cases} 1 & \text{if } Q_j \le S_{i,j} \\ e^{\gamma_{i,j}(Q_j - S_{i,j})} & \text{if } Q_j > S_{i,j} \end{cases}$

$F_{i,j}$	sensitivity of lithology i to lithology j flux
Q_j	flux of the lithology j (in m^2/s)
$S_{i,j}$	inhibition start threshold (in m^2/s)

7. A method substantially as hereinbefore described with reference to the figures.

The Patent Office

23

Application No:	GB 9701296.7	**Examiner:**	B G Western
Claims searched:	1-7	**Date of search:**	8 April 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

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Int Cl (Ed.6): G01V 1/28 1/30 1/40 3/38 9/00 11/00
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Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	EP-0297737-A2 CONOCO N.b. page 2	-
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X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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